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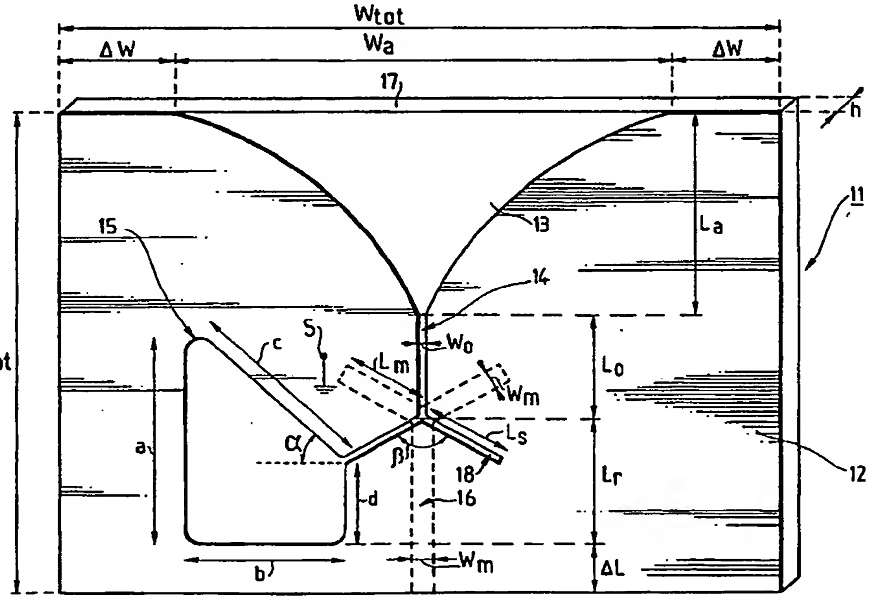
INT CL[5] H01Q 13/08 13/10

(54) Antenna

(57) An antenna 11 is arranged to receive low intensity radio signals over a wide range and in a low band, the antenna being designed to be installed on board a moving platform, and more particularly on a satellite. The antenna comprises a slot line 14 having an end section 13 with a flared profile to form, for example, a Vivaldi antenna. The slot line has an open circuit termination 15 which provides impedance matching so that a separate matching circuit is not required between the antenna and an associated low noise amplifier. A plurality of antennas may be disposed in an array to constitute an interferometer listening system for radio signals.

FIG.4



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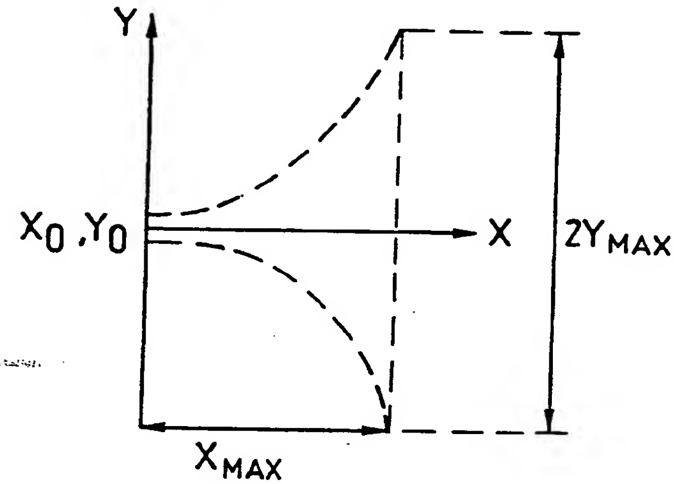


FIG.1A

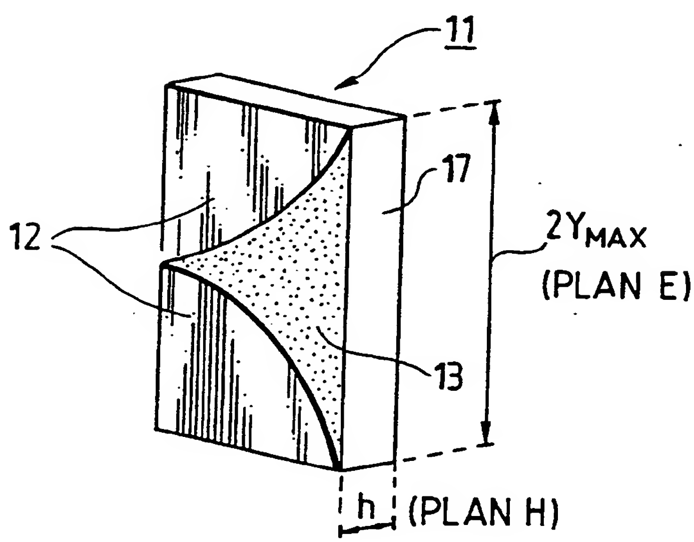


FIG.1 B

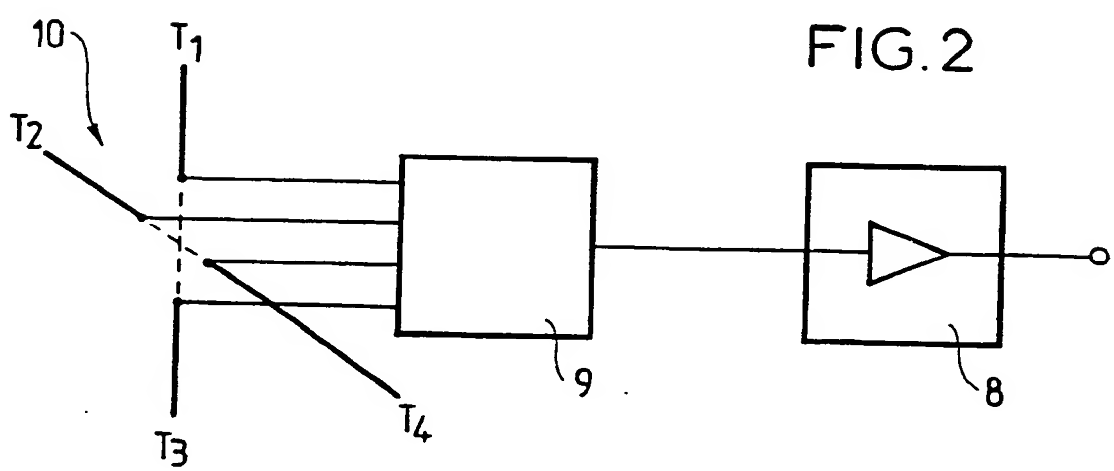


FIG. 2

FIG.3

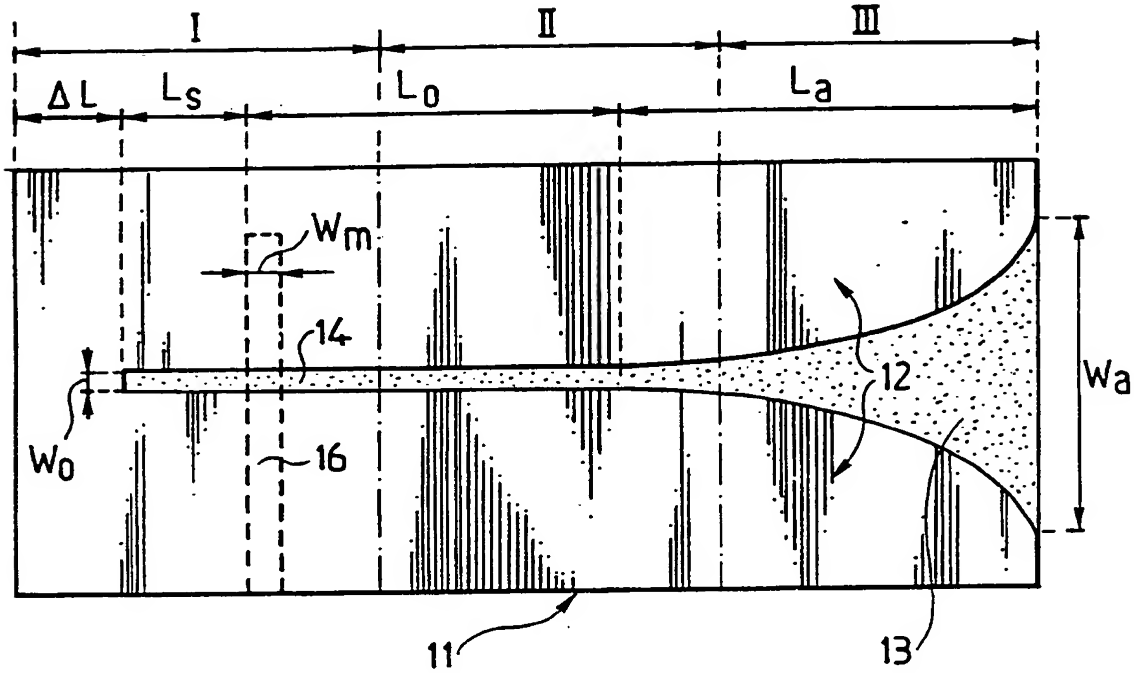


FIG.11

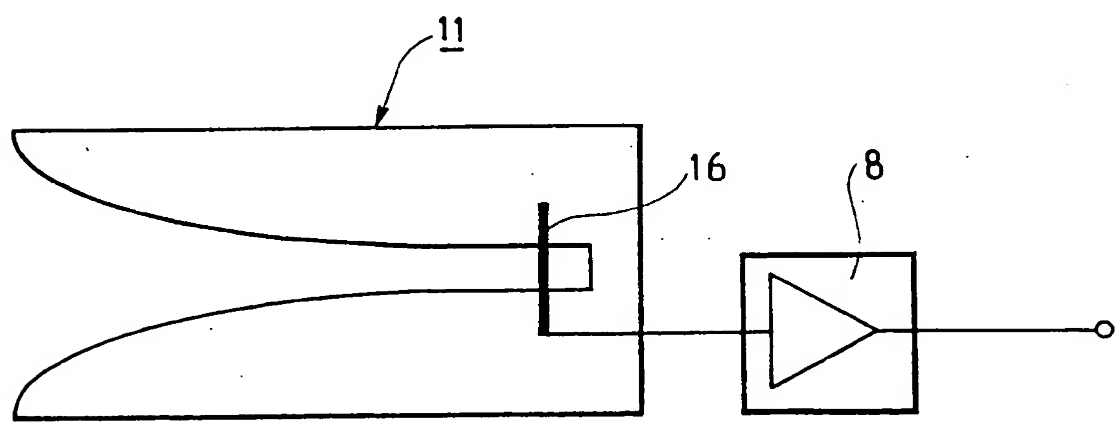


FIG.4

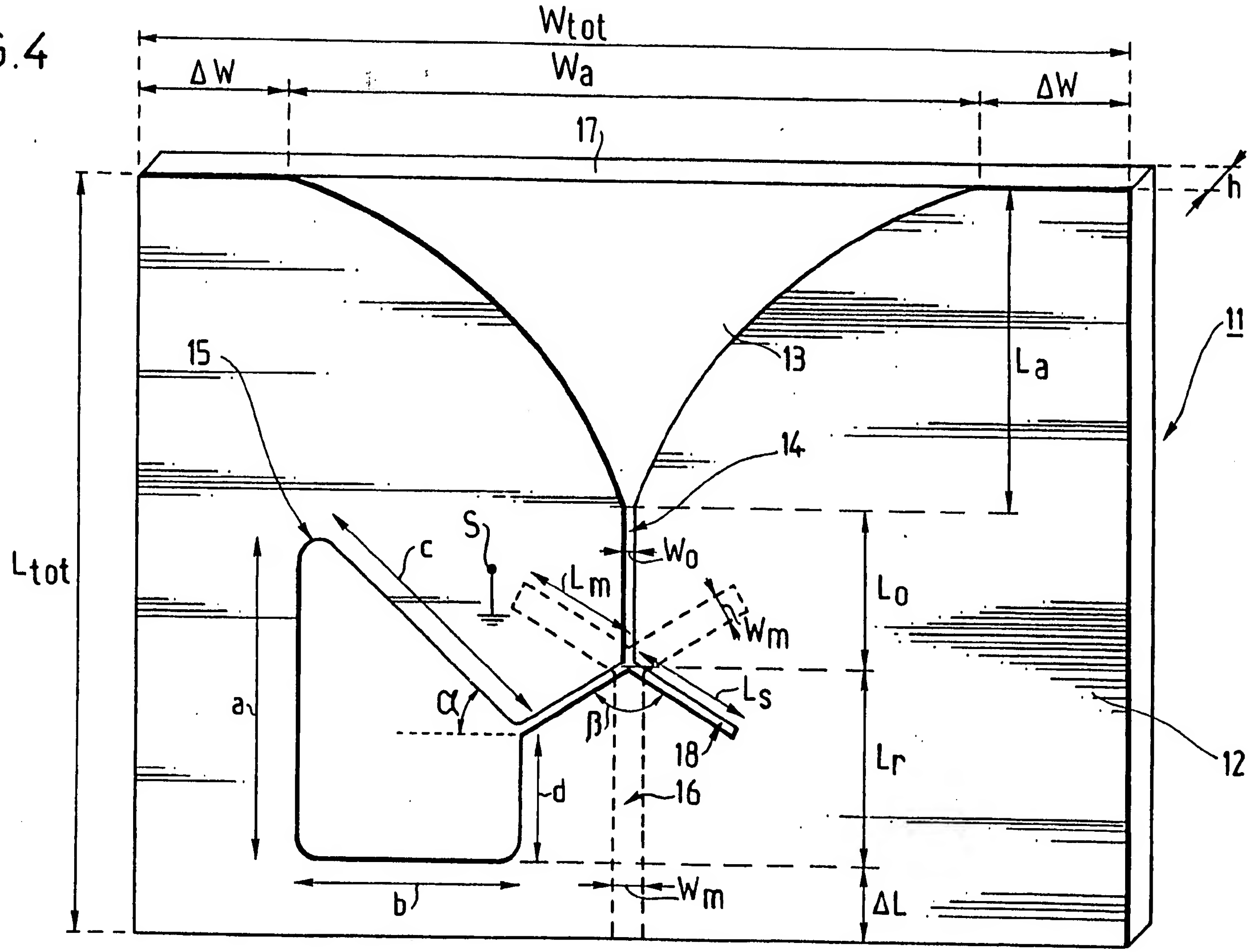

Wtot
Wa
ΔW
ΔW
17
h
11
15
13
La
14
S
c
Wo
Lm
Wm
Lo
Ltot
a
α
β
Ls
18
12
Lr
d
16
b
Wm
ΔL

FIG.5

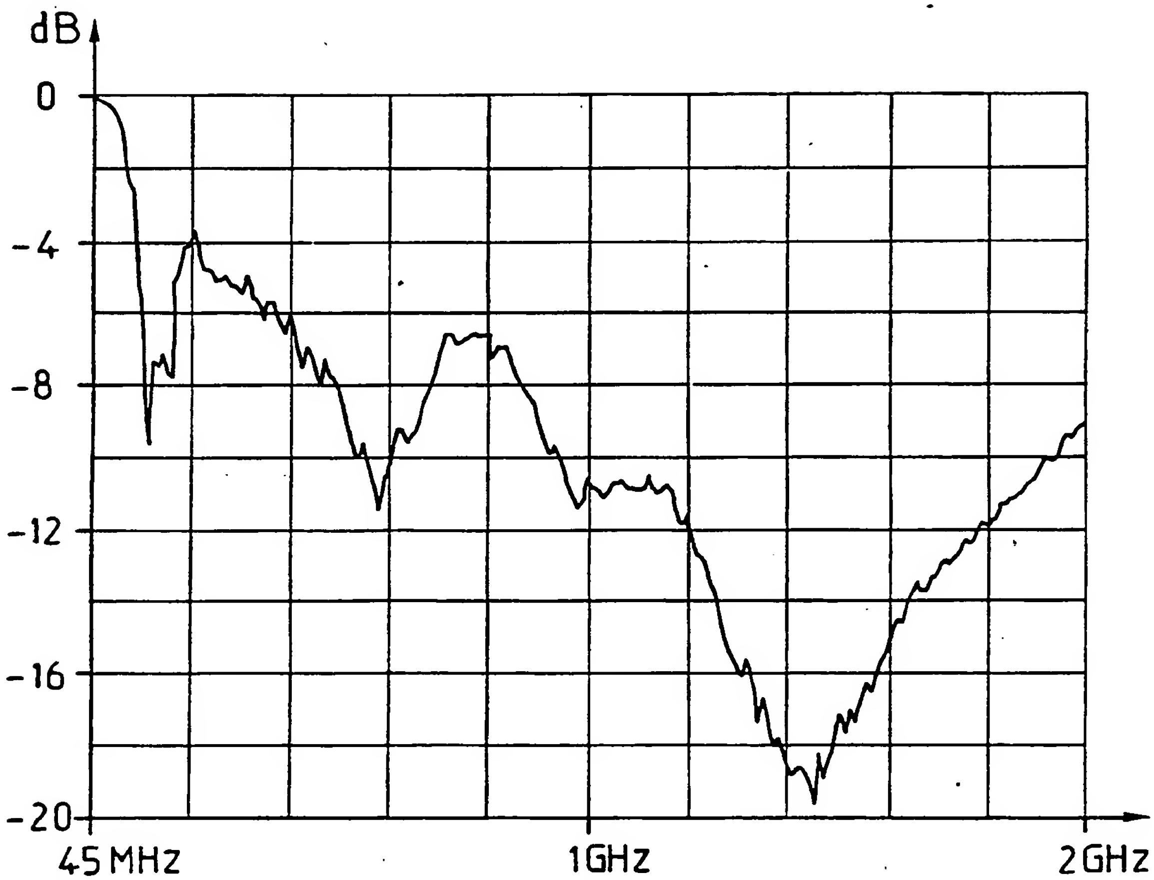


FIG.6A

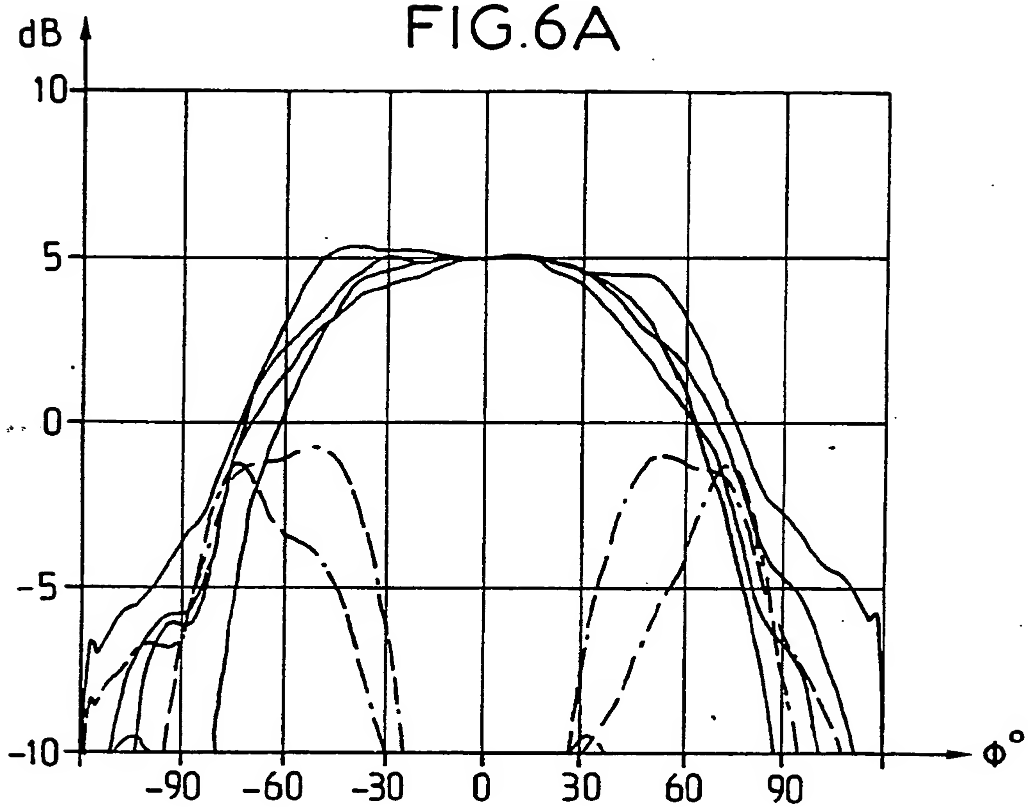


FIG.6B

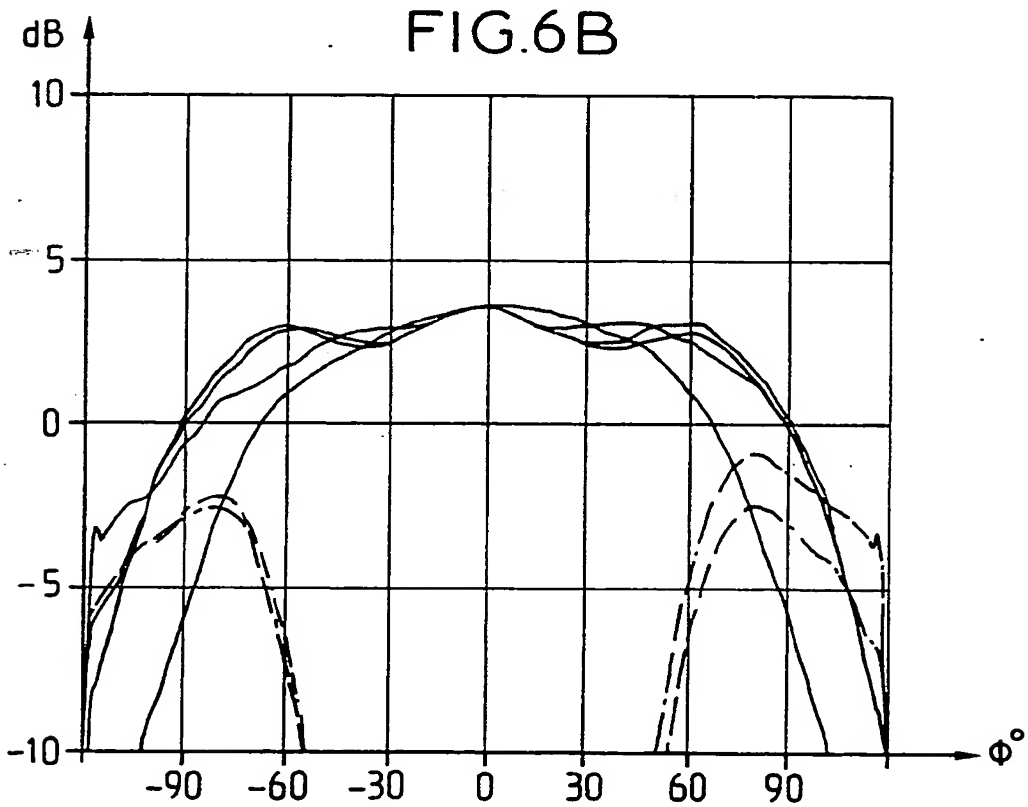


FIG.7A

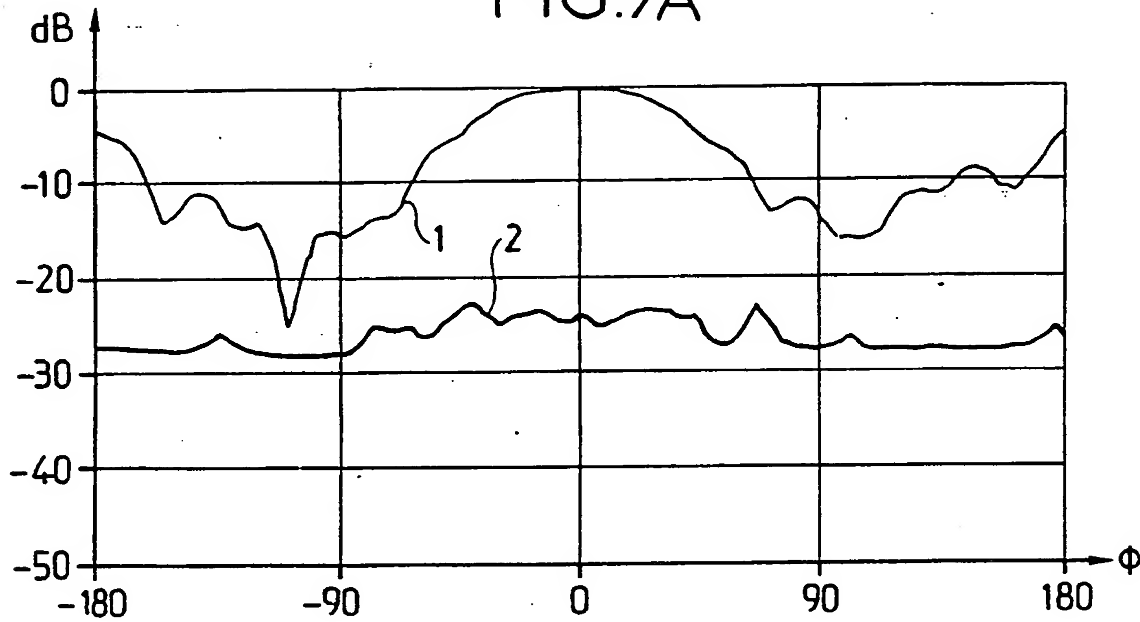

dB
0
-10
-20
-30
-40
-50
1
2
Φ°
-180
-90
0
90
180

FIG.7B

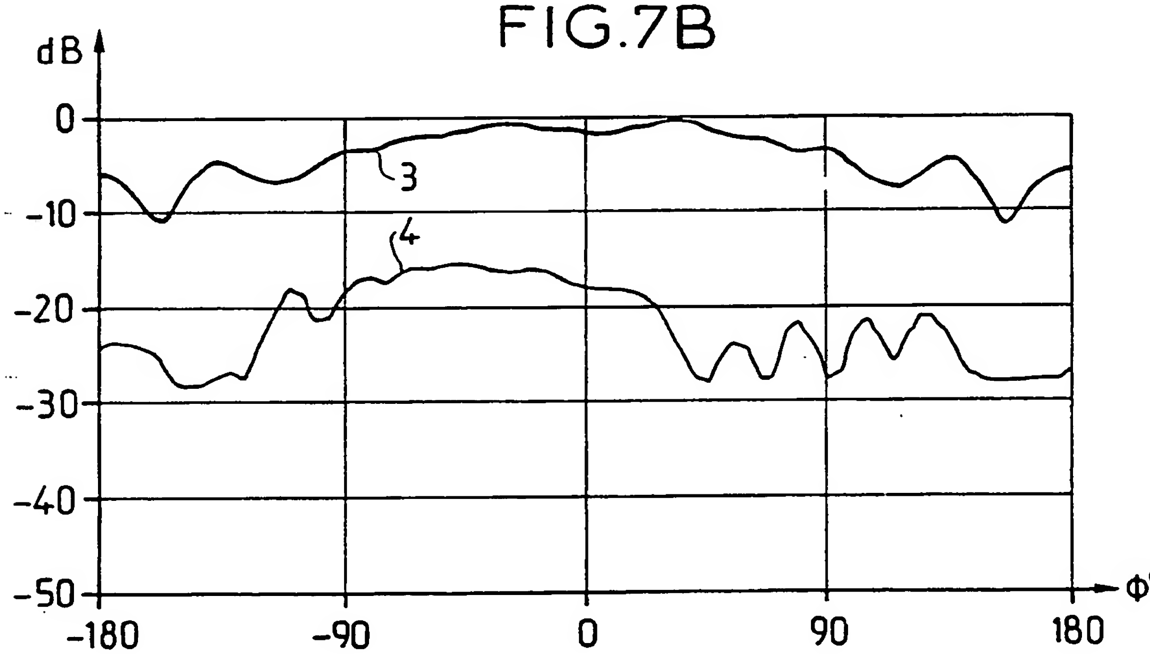
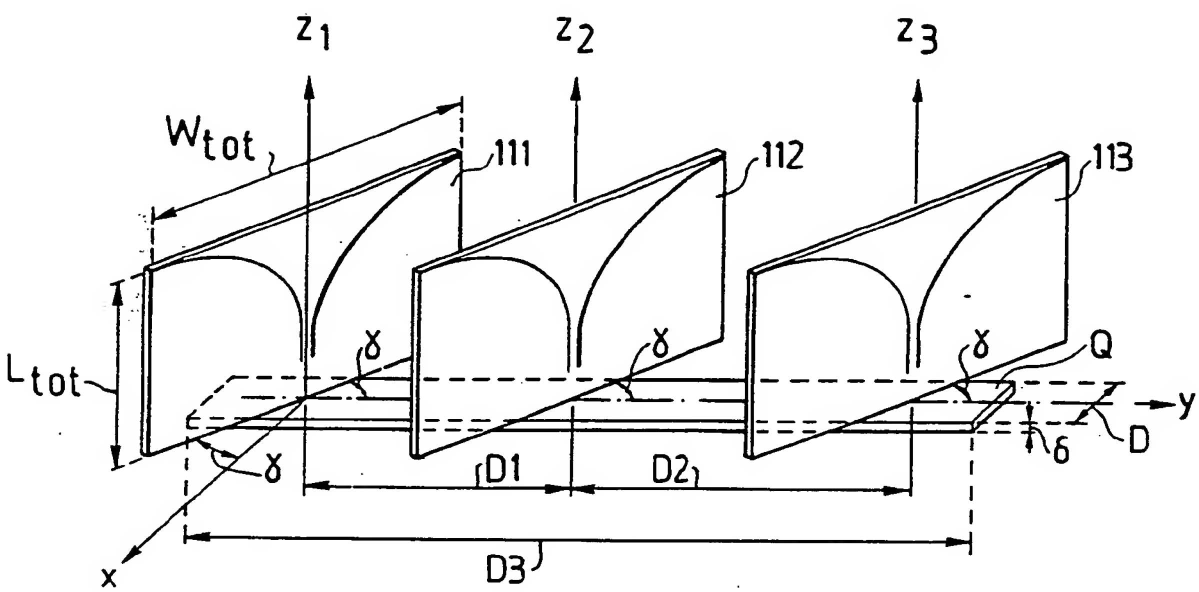
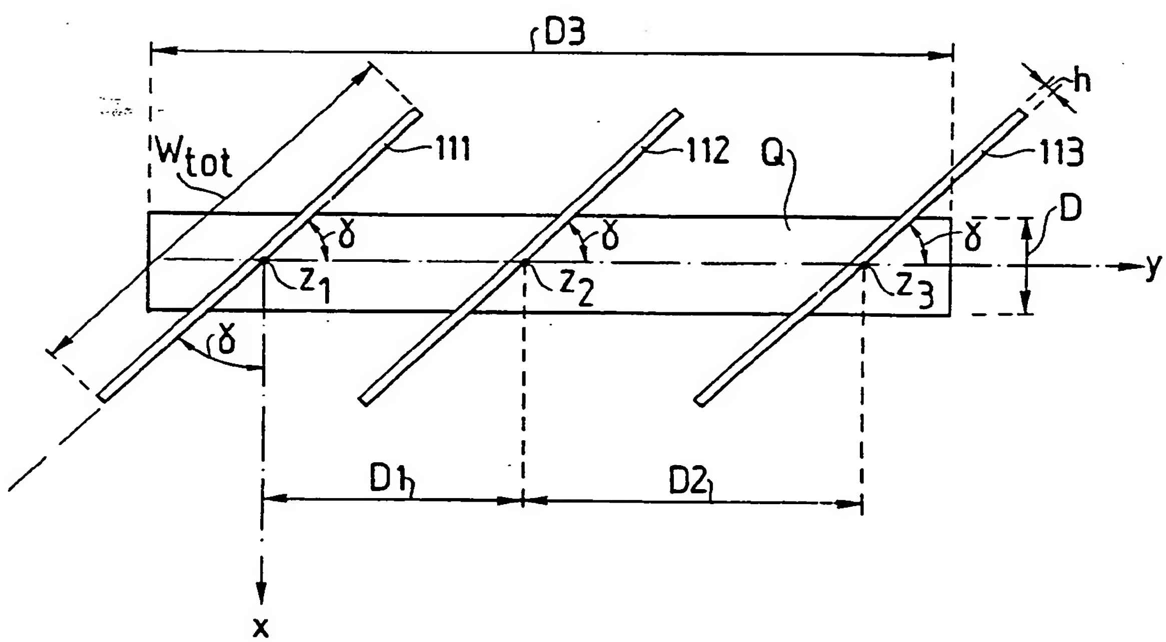

dB
0
-10
-20
-30
-40
-50
3
4
Φ°
-180
-90
0
90
180

FIG.8A



z_1
z_2
z_3
W_{tot}
111
112
113
L_{tot}
γ
γ
γ
γ
Q
y
D
δ
D1
D2
D3
x

FIG.8B



D3
h
W_{tot}
111
112
Q
113
D
γ
γ
γ
γ
z_1
z_2
z_3
y
D1
D2
x

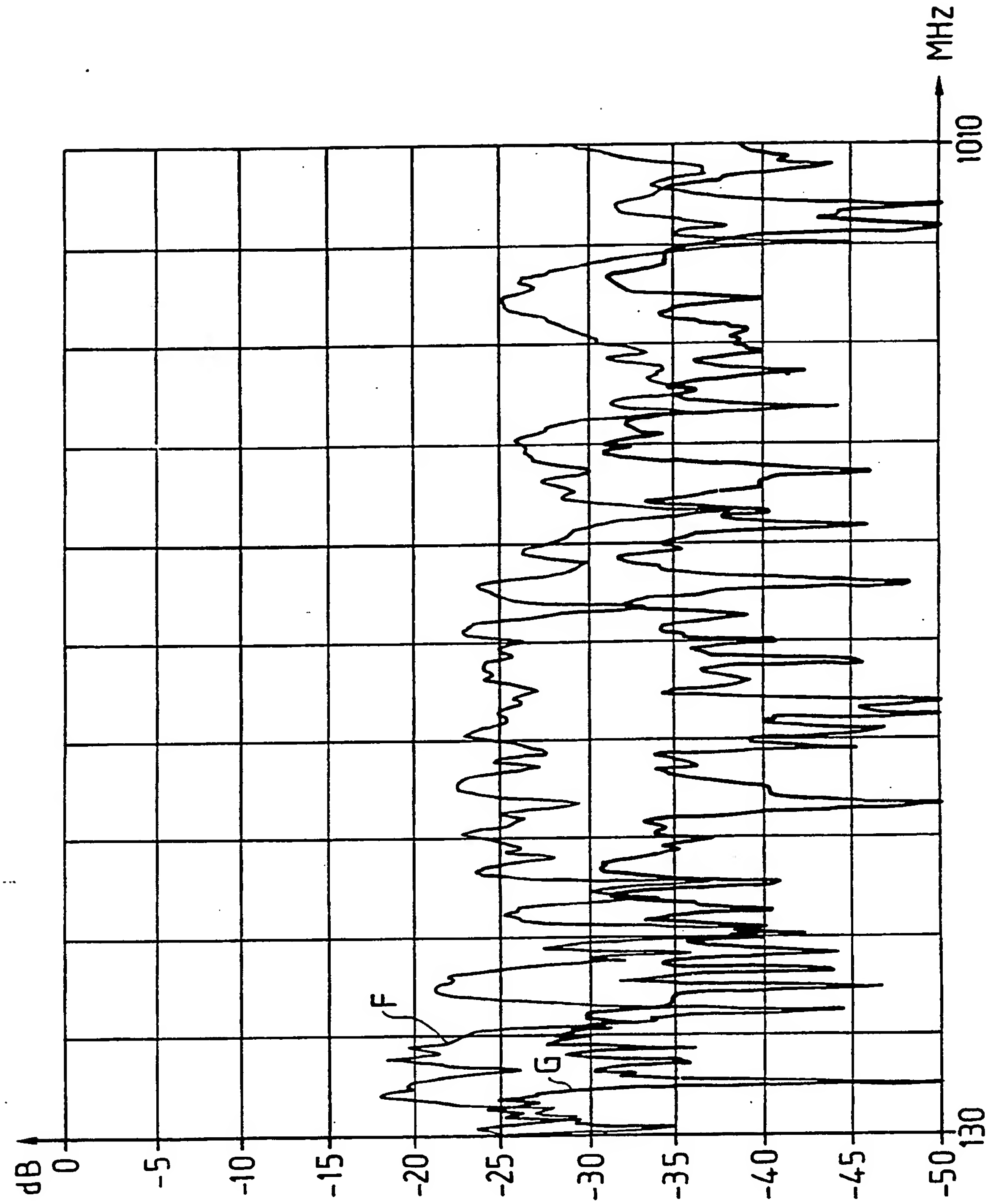


FIG.9

FIG.10A

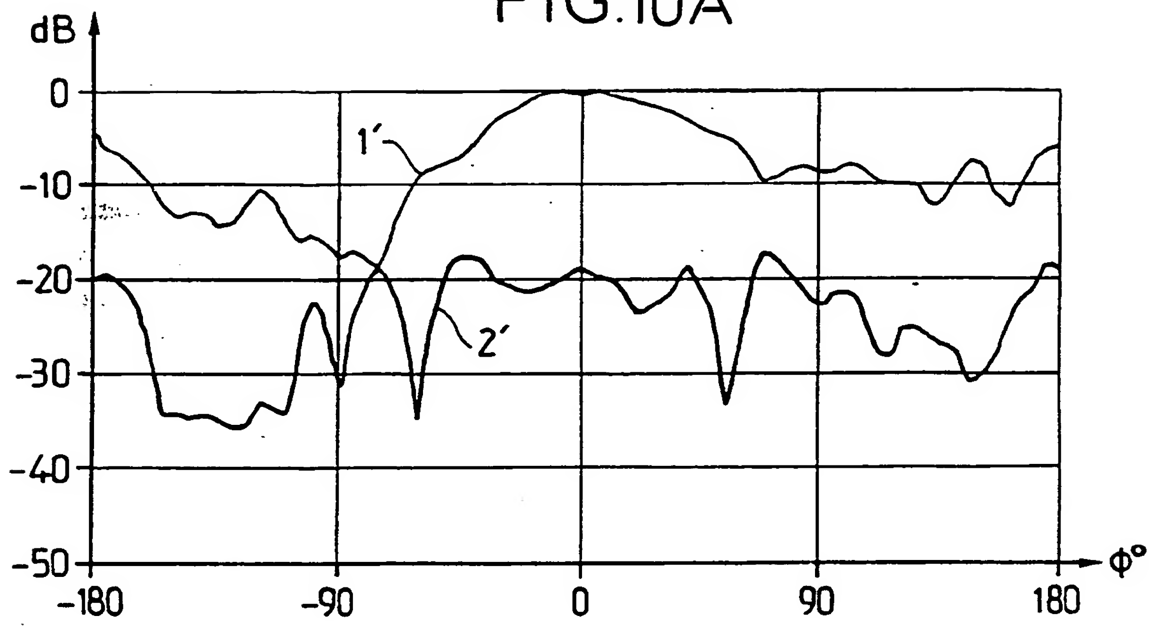
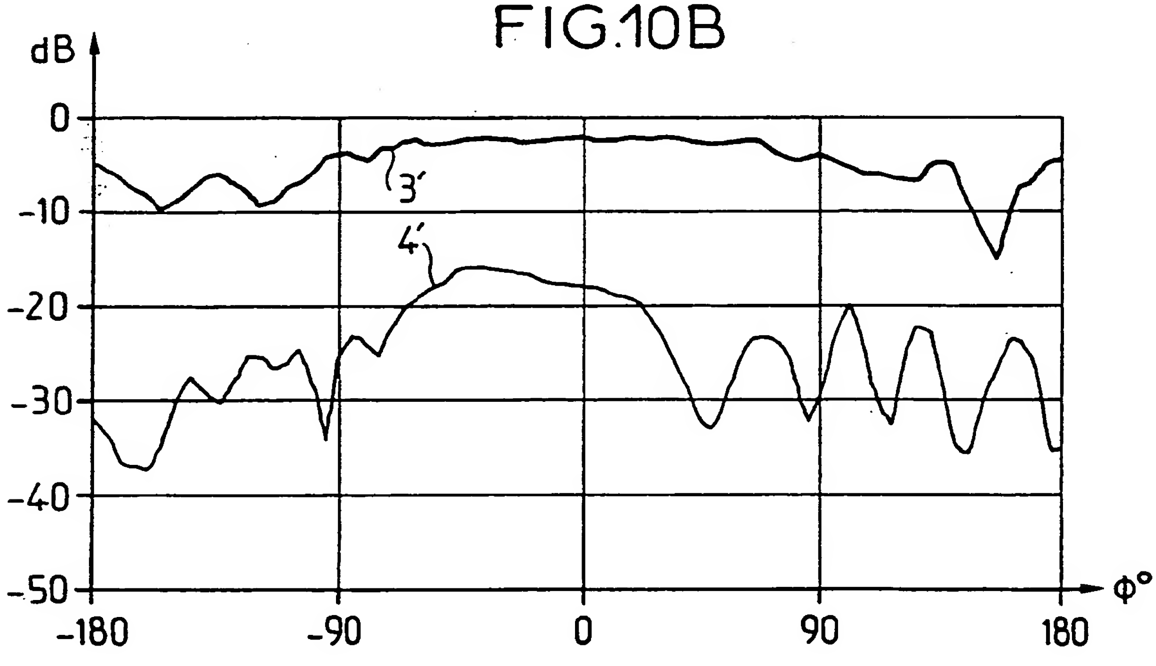


FIG.10B



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A WIDEBAND AND LOW BAND LISTENING INSTRUMENT FOR SPACE APPLICATIONS

The invention relates to equipment for receiving electromagnetic waves, and in particular to equipment designed for use on board a moving platform. In particular, the invention relates to equipment for listening to radio signals over a very wide frequency band, and situated in the low radiofrequency band, between a few tens of MHz to a few GHz, for example. The invention is more particularly adapted for being installed on board a space platform, and in particular satellites, but it may also be fitted to aircraft, ships, land vehicles, etc.

The listening frequency range under consideration lies in the VHF-UHF band, and the person skilled in the art knows the antennas that are generally used therefor. The most commonly used antennas are wire antennas. At such relatively low frequencies, wire antennas are large in size, and this penalizes mass and bulk on board a satellite. In addition, specifically because of the large bulk, they need to be folded up for storage and while a satellite is being launched, subsequently being deployed once the satellite is finally in orbit. This requires complex stacking and deploying mechanisms to be provided which are expensive, bulky, heavy, and furthermore subject to possible breakdown when actuated once a satellite has been put into orbit.

Wire antennas have been known for a long time, constitute the subject matter of numerous studies, and have been used widely because of their initial simplicity. Components therefor operate in one of two modes: either resonant mode for monopoles, dipoles, turnstiles or the like, such that an element of that kind has stable impedance characteristics only over a fairly limited frequency band; or else travelling mode, as applicable to helical type solutions.

It can clearly be seen that the first type of solution is resonant and therefore of limited passband. Using the concept in low bands (100 MHz) requires dipole lengths that

are close to 1 meter, given that wavelength is inversely proportional to operating frequency.

A large amount of work on the second type of solution (the helical type) has made significant advances possible:

multifrequency, interdigitated helices;
non-regular geometries; and
multiple feed modes.

It is thus possible to extend the natural capabilities of solutions of that type to larger-band behavior (≈ 50% to 60% passband) or to multifrequency operation. Nevertheless, the result is well below the performance looked-for from the instrument constituting the subject matter of the invention.

Numerous other types of antenna have been developed, firstly on the basis of a major requirement for an enlarged passband, and secondly from the desire to have radio characteristics that are as stable as possible with frequency. Some are mentioned below, together with comments about their characteristics with respect to the mission that the invention is expected to satisfy.

Thick antennas, e.g. biconic antennas and triconic antennas (where the triconic antenna is a monopole version of the triconical antenna designed by Schelkunoff).

Antennas that are said to be independent of frequency, which means that their behavior remains substantially constant with frequency, e.g. conical or planar spiral antennas or antennas having a scale factor $\underline{z}$ that is close 1.00 so as to obtain a wideband structure.

The following table summarizes qualitatively the characteristics of antenna solutions briefly summarized above:

<u>WIRE ANTENNAS</u>

<u>Dipole</u>

size ≈ $\lambda_0/2$
linear polarization

resonant impedance F (length, diameter)
gain ≤ 2 dB
coaxial feed + balun
narrow band

Turnstile

size ≈ $\lambda_0/2$
polarization:
- twice linear
- circular

resonant impedance
gain ≤ 2 dB if no ground plane
coaxial feed + balun
narrow band

CONICAL ANTENNAS

Biconic

size > $\lambda_0/2$
linear polarization
behavior close to that of the dipole antenna
implementation: biconic antenna or biconical horn
resonant impedance that varies as a function of θ.

Conical monopole antenna

1/2 biconical antenna on ground plane
size ≈ $0.10\lambda_0$ to $0.50\lambda_0$
behavior stable over $\theta_0 \approx 60°$ (± 30°)
wideband ability: ratio of 3 to 5

Inverted cone antenna

dual of conical monopole antenna
"optimum" geometry
$\phi/2 = 20°$ (vertex angle of the inverted cone)
D = 0.7 cm (width at the base of the antenna)
L > $0.25\lambda_0$ to $0.30\lambda_0$ (where $\frac{1}{2}D = L\cos(\phi/2)$, from which the length of the sloping face of the inverted cone antenna can be deduced).

With the optimum geometry for the inverted cone antenna, behavior can be observed that is stabilized with

respect to impedance over bands of 5 to 10, or thereabouts. Nevertheless, the appearance of the radiation pattern varies significantly as a function of frequency.

SPIRAL ANTENNAS

Various planar geometries and also various three-dimensional solutions exist. The lowest working frequency is commonly set by an electrical path and leads to a condition of the type: $\pi \times \text{diameter} \approx \lambda_0$.

High ratios are available and such elements are commonly used over bands in the range 10 to 20.

It can be seen that for the intended application of the invention, none of the solutions known in the prior art is suitable simultaneously for satisfying the constraints of installation on board a moving platform and in particular on board a satellite, together with the radio objectives relating to sensitivity, detection threshold, bandwidth, low frequency, antenna radiation pattern, and in particular antenna behavior as a function of frequency.

To describe the problem in greater detail, the invention seeks to provide an instrument for listening to radio signals using appropriate sensors that operate over ranges of low frequencies and that have very large passbands (e.g. a few MHz to a few GHz). Such sensors are required to operate on space vehicles that may be small in size, and that are subjected to severe dimensional constraints:

very small maximum size;

special configuration during launching;

deployment once in orbit; and

configuration in orbit.

The required radio performance must be guaranteed by incorporating all of the component parts of the satellite:

satellite body;

solar panels; and

stabilizing appendices.

Still within the same frequency range, a second requirement consists in achieving alignment between a plurality of sensors so as to implement them in an array. The following problems therefore need to be dealt with:

1/ All of the installation problems that relate to the configurations as stored in orbit and also to the structural elements required for holding and displacing the antennas. It is clear that bulky elements are highly penalizing from the point of view of accommodation and that implementing such elements will have severe repercussions on the complexity and on the mass of the vehicle, both of which are particularly critical in space applications.

2/ The radio behavior of antennas connected in an array in the presence of the remainder of the structure, e.g.: the displacement arm, the solar panels, the body of the satellite. Severe disturbance of the quality of radiation associated with electromagnetic coupling mechanisms can render the entire mission impossible. Certain types of radiator that have radio characteristics that appear satisfactory when a radiating element is properly disposed relative to its ground plane lend themselves very badly to being installed on a satellite structure made up of a discontinuous assembly of elements that cannot guarantee an appropriate electrical function of the ground plane type.

Furthermore, at the frequencies under consideration, the structural elements making up the satellite all lie in ranges of sizes suitable for being intrinsically diffractive (e.g. $0.5\lambda_0$ to $3\lambda_0$).

Thus, an antenna that is not properly designed will give rise to currents in all of the structures of the platform, which currents can only be considered as constituting interference. Such currents, in application of the reaction principle, in turn induce currents in the antenna, until an equilibrium situation is established between inducing and induced currents.

The magnitudes that are therefore no longer guaranteed

are the following:

antenna impedance; and

radiation pattern.

It is therefore important to pay particular attention to the way in which the radiating element is designed whenever a low frequency application is required on a space vehicle, or elsewhere, e.g. on any other moving platform of similar dimensions: aircraft, truck, ship, etc.

There follows a description of one example of a prior art space listening instrument for use over a large band at low frequencies. It is difficult to discover everything that takes place in this field since it is a field where players remain rather discrete as to their technical advances. The context of the mission is a low band application: about 30 MHz to about 500 MHz, for which it is desired to provide a sensor.

The simplest conventional design is shown in Figure 2 and it consists in using:

a) a turnstile antenna (10) made up of two crossed dipoles (T_1, T_3; T_2, T_4); and

b) an associated active band matching circuit (9) located upstream from a low noise amplifier (8).

In order to avoid having prohibitive bulk, it is required that the turnstile shall have a total length that does not exceed 500 mm. That solution is indeed simple, but it suffers from the following drawbacks:

omnidirectional radiation, and therefore <u>a fortiori</u> on the structures, thereby giving rise to very severe disturbances in respect of:

radiation pattern quality;

transfer amplitude and phase;

impedance; and

coupling with the other elements;

an overall matching problem thus associated with quality of the transmission factor which is evaluated in terms of signal-to-noise ratio, for example, at the output of the wideband receiver.

For a design based on crossed dipoles (T_1, T_3; T_2, T_4), antenna matching is achieved by means of an active circuit (9); in which case two major problems arise:

the transfer function (S_{21}) is highly penalized with respect to power firstly by mismatching and secondly by losses in the matching circuit; and

the active circuit (9) used provides a non-negligible contribution to noise, thereby degrading the received signal even before it reaches the wideband low noise amplifier (8).

Overall, using a concept derived from ground applications, but not redesigned for space applications, an instrument is obtained that has mediocre sensitivity.

The invention seeks to solve these various problems of the prior art. The above-mentioned problems are global and bring together:

the way in which the antennas are installed on the vehicle;

the overall sensitivity of the instrument obtained in this way; and

the quality of the mission in orbit for a satellite platform (e.g. comprising minimizing coupling, changes in radiation patterns and in impedances as a function of frequency over the listening band, etc. ...).

To these ends, the invention provides a system for listening to radio signals over a very wide listening band that is a low band, the system being designed for being installed on board a moving platform, said system comprising at least one electromagnetic sensor, together with a low noise amplification system associated with each sensor, the system being characterized in that said sensor is derived from a slot line, and said slot line has a profile in which the width of the slot varies along its length. In a variant of the invention, the profile varies linearly. In a preferred embodiment, the profile is exponential and said sensor is a "Vivaldi" type antenna.

In an advantageous embodiment, the maximum width of said slot at the end of the Vivaldi type antenna is of the

order of $\lambda_0/3$ where λ_0 is the wavelength at the lowest frequency of said listening band. According to another particular characteristics, the overall length of said Vivaldi type sensor $L_{tot} \approx \lambda_0/4$.

In a particular embodiment, the overall length of said Vivaldi type sensor $L_{tot} \approx \lambda_0/8$, for a frequency of 100 MHz.

In a particular embodiment, the overall length of said Vivaldi type sensor $L_{tot} \approx \lambda_0/12$ for a frequency of 75 MHz.

In a variant of the invention, the listening system comprises a plurality of electromagnetic sensors satisfying one or more of the characteristics specified above. In application of this important characteristic, said plurality of sensors is constituted as an array for implementing an interferometer system for listening to radio signals, thereby enabling the detected signals to be located. In a preferred embodiment, the various sensors are spaced apart with a distance D between two sensors such that $D > 2 \times L_{tot}$. In a variant, said listening system is a listening and locating system including at least one of the preceding characteristics.

In any event, the invention will be well understood, and its advantages and characteristics will appear more clearly from the following description of various non-limiting embodiments, descried with reference to the accompanying diagrammatic drawings, in which:

Figure 1A is a highly simplified diagrammatic plan view of a Vivaldi type radiating element that is known in the prior art;

Figure 1B is a highly simplified diagrammatic perspective view of a Vivaldi type radiating element known in the prior art;

Figure 2 is an electronic block diagram of a prior art narrow band listening system;

Figure 3 is a highly simplified diagrammatic plan view of a Vivaldi type element for picking up electromagnetic radiation;

Figure 4 is a diagrammatic plan view of a specific example of a Vivaldi type element of the invention for picking up electromagnetic radiation;

Figure 5 is a graph showing impedance matching measurements performed on the Figure 4 device in terms of reflection coefficient (dB) as a function of frequency;

Figure 6A shows gain measurements (directivity) performed on the Figure 4 device at 3.5 GHz, as a function of angle relative to the main radiating axis;

Figure 6B shows gain measurements (directivity) performed on the Figure 4 device at 1.67 GHz, as a function of angle relative to the main radiating axis;

Figure 7A shows antenna radiation pattern measurements with crossed polarization and copolarization for the Figure 4 device as performed at 450 MHz and in the E plane;

Figure 7B shows antenna radiation pattern measurements with crossed polarization and copolarization for the Figure 4 device as performed at 450 MHz and in the H plane;

Figure 8A is a diagrammatic perspective view of one example of an array of Vivaldi antennas of the invention;

Figure 8B is a diagrammatic plan view as seen from above of an example of an array of Vivaldi antennas of the invention;

Figure 9 shows coupling measurements performed on the system of antennas shown in Figures 8A and 8B;

Figure 10A shows the radiation patterns of the antenna in crossed polarization and in copolarization for the array of Figure 8 in the E plane;

Figure 10B shows the radiation patterns of the antenna in crossed polarization and in copolarization for the array of Figure 8 in the E plane; and

Figure 11 is an electronic diagram of a wideband listening system of the invention.

In the various figures, the same references relate to the same elements. The scale of the drawing is not always accurate for reasons of clarity.

Figure 1A is a highly simplified diagrammatic and plan view of a prior art Vivaldi type radiating element, e.g. as disclosed in US patent US-A-5 036 335. The drawing shows the geometrical parameters of a conventional Vivaldi antenna along arbitrary Cartesian axes (X, Y). In the figure, the coordinate origin (X_0, Y_0) lies on the axis of symmetry of the Vivaldi antenna (the X axis), which is also the main radiating axis. The maximum width of the aperture of the antenna is $2Y_{MAX}$, centered on Y_0.

The characteristic of the conventional Vivaldi antenna is the exponential relationship between the width of the aperture of the antenna and its position along the radiation axis X:

$$Y = Y_0 \pm (1 - \exp(aX))$$

where X_0 has been selected to be 0 and where a is an arbitrary constant.

A practical embodiment of a conventional Vivaldi antenna (11) is shown in perspective in Figure 1B. The antenna (11) is made by metallization (12) on a dielectric substrate (13) using slot line technology. A metal ground plane (12) on the dielectric substrate (13) is defined by the exponential curves given in Figure 1A. The aperture of the antenna (17) has the dimensions $2Y_{MAX}$ in the radiation E plane, and the thickness h of the dielectric substrate (13) extends in the radiation H plane.

Patent US-A-5 036 335 relates to improvements in the conventional Vivaldi structure for obtaining a transmission band of 1 GHz to 40 GHz while maintaining the structure shown in Figures 1A and 1B. The improvements proposed relate mainly to the coupling between the feed line (not shown) and the slot line of the Vivaldi radiating element. It may be observed that unlike the system of the invention, that prior art antenna has to operate in transmission only and in a frequency band that is relatively high. In contrast, the listening system of the invention operates in reception only and operates at frequencies that are lower by one or two orders of magnitude. Using Figure 3 to compare

the prior art antenna with the antenna of the invention shows an unexpected selection of design parameters for performing the mission intended for the invention.

Above-mentioned Figure 2 is an electrical block diagram of a conventional listening system. In the prior art, the antenna most commonly used for a listening system is a turnstile (10) made up of two crossed dipoles (T_1, T_3; T_2, T_4). The signal picked up by the dipoles is then conveyed to a low noise amplifier (8) via an impedance matching circuit (9). The problems with that arrangement have already been mentioned above.

Figure 3 is a highly simplified diagrammatic plan view of a Vivaldi type electromagnetic radiation pickup element on which the geometrical parameters of the various characteristics of the device are marked, as are zones (I, II, III) that correspond to different functions within the antenna itself.

The zone I is a transition zone from a first propagation line that feeds the antenna: a microstrip (16), a strip line, a waveguide; towards the propagation mode on the slot line (14). This zone is subject to considerable discontinuities and it is essential to manage it properly in order to guarantee wideband behavior from the impedance point of view.

The zone II is the zone in which propagation takes place in slot line mode. This portion serves to convey the feed energy towards the radiation zone for an antenna being used in transmission, or in the case of the invention, from the aperture of the antenna towards the low noise amplifier.

Zone III is the transition zone to radiated mode, and its structure enables very wide passbands to be obtained. In transmission, the antenna provides unidirectional radiation that is linearly polarized to match the distribution of the electric field between the two areas of metallization.

The characteristics of the antenna are controlled by acting on the geometry of the antenna, by selecting values

for the various parameters marked in the figure. Coupling in zone I is a function of the relative disposition and of the width W_m of the microstrip (16) and the width W_o of the slot line (14). The length L_s of the electrical path between the coupling region and a short circuit of the slot line is selected to optimize the impedance of the coupling as a function of wavelength. The length L_o of the slot line between the coupling region and the beginning of changing profile in zone III is important for the compactness of the antenna (11). Finally, the behavior of the antenna when radiating or when receiving, and in particular its bandwidth, depend on the parameters of zone III:

the length of the termination (parameter L_a);

the aperture of the termination (parameter W_a); and

the nature of the profile of the metallization (12) selected for going from propagating slot mode at the aperture W_a.

Numerous profiles may be proposed:

linear, the most simple but not the most compact;

exponential, giving rise to the Vivaldi concept (known to the person skilled in the art as the "Vivaldi slot antenna"); and

other, in which the distribution corresponds to seeking particular optimization: performance/size.

Certain aspects appear most advantageous in the applications envisaged for the invention. In particular, the advantage of having energy propagate in slot line mode is to confine the waves in a very small volume that is highly insensitive to the outside environment, thereby minimizing possible interfering coupling with the structures of the platform or between elements in an array. The limit conditions for a line of this type are such that the field E extends hardly any distance beyond the metallization and the outside environment does not have any effect on the propagation characteristics and on the distribution of the radiated fields.

The antenna of the invention also makes use of the unidirectional radiation characteristics of such a device. Such a longitudinal mode antenna provides mode transition between slot line mode and free space mode in the following manner: the electric field **E** that propagates naturally along the slot flares in the portion (III) until it finds itself propagating in free space. This natural and geometrical transition has no adverse effects on currents, on structures, or on the condition of the ground plane. This is a major advantage over antennas based on wires, microstrips, or on radiation conditioned by creating currents over surfaces.

Thus, by its very nature, an antenna based on a longitudinal and propagating mode of radiation is characterized by a certain number of advantages that can be specified as follows:

low back radiation;

reduced disturbance of surrounding or supporting structures; and

greater ease of array building because of the low level of coupling between the various elements.

The values chosen for the various parameters enable an antenna of the invention to be distinguished from a known Vivaldi antenna optimized for telecommunications applications.

In the context of telecommunications applications, the "conventional" dimensions for Vivaldi or slot type antennas are derived as a function of the following objectives:

a) obtaining a standing wave ratio of about 1.5, giving a reflection coefficient of -15 dB; and

b) stabilizing the radiation pattern over the frequency band.

As a result design rules have been established that satisfy the above-described criteria. Numerous authors have analyzed and implemented various different geometries, some of which are described in the following documents:

(1) Schuppert, B. IEEE, MTT, Vol. 36, No. 8, August 1988, pp. 1272-82: Microstrip - slotline transitions, Modelling and experimental investigation.

(2) Simons, R.N. et al. (NASA) IEEE - APS symposium digest, Chicago USA, July 1992: Non-planar linearly tapered slot antennas with balanced microstrop feed.

(3) Schaubert, D.H. - Proceedings JINA 1990 (Journees Internationales de Nice sur les Antennes), Nice, France, pp. 253-65, November 1990. End-fire slotline antennas.

Those prior art efforts lie in the following ranges of geometrical parameters:

antenna aperture: W_a

$0.35\lambda_0 \geq W_a \geq p\lambda_0$

profile length: L_a

$0.70\lambda_0 \geq L_a \geq q\lambda_0$

where L_a and W_a are as defined in Figure 3, and where p and q may have values of up to several tens.

It is clear that in the low frequency ranges to which the invention applies, if the above design rules are used blindly, they give rise to insurmountable problems of size and thus of installing antennas on mobile platforms, for example, if F_0 = 300 MHz, then $W_a \approx$ 350 mm to 400 mm; total length $L_{tot} = L_a + L_o + L_s + \Delta L = 700 + (L_o + L_s + \Delta L) \approx$ 800 mm.

If operation at a lower frequency is envisaged, then the size of the antenna varies linearly with wavelength. The above example at 100 MHz is convincing and dissuasive: F_o = 100 MHz, $W_a \approx$ 1050 mm, $L_a \approx$ 2250 mm.

One of the ideas of the invention is thus to propose a design of antenna that is not associated with the impedance criterion but with the quality of the listening instrument in terms of sensitivity. A Vivaldi antenna is essentially a wideband transition such that the overall behavior of the instrument can be established as follows, unlike narrowband systems. Thus, a loss of 2 dB to 3 dB in the transmission factor of the antenna can be considered as being reasonable, since under such circumstances both systems must be compared

in the same circuit plane and for the same performance in terms of signal-to-noise ratio.

The practical advantage of the invention is demonstrated below with reference to the following figures that show various embodiments, and in terms of measurements performed on the embodiments.

Figure 4 is a diagrammatic plan view of a specific example of a Vivaldi type electromagnetic radiation sensor element of the invention, in which the various parameters have been optimized as a function of the intended applications: listening mission over a very wide band at low frequency, in the range 200 MHz to 2 GHz, combined with compactness and sensitivity suitable for installation on board a moving platform and in particular on a micro-satellite. The example shown in this figure is fed by means of a strip line (16) from a Y-Y type transition that is sized at around 500 MHz. Thus the geometry of the antenna is such that $W_a \approx 0.35\ \lambda_{200MHz} = 520$ mm. The geometry of the length $L_{tot} = L_a + L_o + L_s + \Delta L$ is very compact because a requirement has been applied of not exceeding 330 mm overall, so as to be compatible with installation on a microsatellite.

Under such circumstances, 330 mm represents only $0.22\ \lambda_{200MHz}$, and is thus much less than the conventional size that is close to the wavelength.

Figure 4 reproduces certain parameters from the preceding Figure, and the precise values thereof are given in millimeters in the following table:

L_{tot}	L_a	L_o	$L_r+\Delta L$	L_s	L_m
330	200	60	70	30	30

W_{tot}	W_a	W_o	ΔW	h	W_m
600	570	1	15	6.1	8.38

a	b	c	d	$\alpha(°)$	$\beta(°)$
163	53	60	28	45	120

Compared with the preceding figure, the present example includes certain elements that tend to enlarge the passband and to improve coupling between the various propagation modes, thereby improving detection sensitivity in the intended applications. Such structures are known to the person skilled in the art, and the principles of some of them are described in the above-mentioned US patent, apart from the exact dimensions which are selected by the designer as a function of the particular mission that is to be performed. For example, the metallization (12) includes a slot line (14) which terminates in a fork to two branches that are at an angle β apart where $\beta = 120°$, each of the branches having the same width as the line (14). One of the branches is terminated by an open circuit (15), constituted by a non-metallized area situated at $L_s = \lambda/4$ from the fork. The geometry of this open circuit is designed to provide an impedance-matched termination for slot line mode propagation. The other branch terminates in an open circuit, likewise at a distance $L_s = \lambda/4$ from the fork (sized for 500 MHz).

The strip line feed line is terminated in similar manner by a fork, having one branch which terminates in a short circuit S at a distance $L_m = \lambda/4$ from the fork, and having another branch that terminates in an open circuit, likewise at a distance $L_m = \lambda/4$ from the fork. λ is a selected wavelength close to the lowest listening frequency.

The extreme compactness of the example described can be seen, since its overall dimensions are quite different from those encountered in antennas of the same type in the prior art. Above all, it will be observed from the following figures that the measured radio performance of this device is excellent.

Figure 5 is a graph of impedance matching measurements performed on the Figure 4 device plotted as a function of frequency. Before describing the graph, it is appropriate to situate performance as influenced by impedance matching by means of a simple table that provides a clear context for the performance of the sensor.

Reflection coefficient (dB)	Standing wave ratio	Transmission losses (dB)
-5	3.57	-1.65
-4	4.40	-2.20
-3	5.66	-3.00
-2	8.72	-4.33

For the listening system of the invention, satisfactory sensor performance consists in accepting transmission loses of up to 2 dB to 3 dB. The table thus puts us in the range -3 dB to -4 dB for reflection coefficient. Beyond that, it can be assumed that the sensor continues to operate and that its behavior should be measured in terms of sensitivity, and thus in association with the low noise amplifier (8) with which it is associated in the reception system.

Figure 5 shows the reflection coefficient as a function of the frequency of the Figure 4 device, over the frequency range 45 MHz to 2000 MHz. It can clearly be seen that there is a -4 dB maximum match in the band 200 MHz to 2 GHz, in compliance with the initial requirement for the looked-for performance. In addition, the impedance response is well centered around 500 MHz which constitutes a special matching zone for the circuits since a coefficient of about -10 dB is obtained at around 500 MHz. Beyond that there can be found a conventional wideband response which continues without difficulty to 2 GHz.

It may also be observed that the device does not become thoroughly reactive (too great a reflection coefficient) until very low working frequencies are encountered of the order of 40 MHz to 50 MHz. If a mismatch of up to -2 dB can be accepted in the reflection coefficient, then it can clearly be seen that the antenna is capable of operating down to about 100 MHz. In these ranges, such an extension is considerable and gives rise to an overall additional transmission loss of 1 dB (i.e. when the instrument is seen as a whole in the context of the listening system of the invention), for constant size that is limited by geometry in which W_a is optimized for 200 MHz, and which is particularly compact in length, being of the order of only 0.12λ at 100 MHz.

Figures 6A and 6B show gain measurements as a function of angle relative to the main radiation axis (directivity) performed on the Figure 4 device respectively at 3.5 GHz and at 1.67 GHz. In each of Figures 6A and 6B there are four solid line curves that represent four planes in which measurements were taken, the various planes being separated by angular rotation about the main radiation axis (azimuth). Dashed lines are used to designate the presence of crossed-polarization lobes, which lobes nevertheless remain well below the amplitude of the main lobes. These figures show that gain and directivity performance as a function of frequency is good, since the parameters change little from Figure 6A to Figure 6B.

The first family of curves shows behavior that is stable in frequency and that is of the unidirectional type, i.e. at such frequencies, the antenna radiates in a half plane with excellent qualities of crossed polarization symmetry and purity. At these frequencies the antenna is "naturally directional", i.e. the conditions $W_a \approx 0.20\lambda_0$ and $L_a \approx 1\lambda_0$ suffice to achieve good directivity at these frequencies.

The antenna of Figure 4 has also been measured at much lower frequencies, and Figures 7A and 7B show the

measurements performed at 450 MHz on the two main sections, respectively the E plane and the H plane. Each figure shows two curves: an upper curve (1,3) represents measurement with main polarization (copolar), while the lower curve (2,4) represents measurement with crossed polarization.

The measured behavior corresponds to our theory of antenna design. From these measurements we observe that in the E plane section shown in Figure 7A, the copolar radiation maximum (curve 1) is at 0° with small back lobes that are -5 dB to -10 dB down on the maximum. The cross-polarization radiation maximum (curve 2) lies in the range -15 dB to -20 dB beneath the copolar radiation.

In the H plane section given in Figure 7B, the antenna patterns are enlarged and thus less directional, and they demonstrate good polarization isolation (≤ 10 dB or even 15 dB between curves 3 and 4).

At these frequencies, the patterns are naturally less directional because of the compactness of the geometry of the antenna, particular in the H plane: the patterns that we have measured at 300 MHz and at 220 MHz (not shown) are entirely satisfactory. All of these measurements show realistic and acceptable behavior for copolar radiation as compared with theory, given that compactness is considered as being the deciding parameter, since it is vital for a system that is designed to be installed on a moving platform. It is recalled that at 200 MHz, the overall length of the antenna is less than $0.22\lambda_0$. It is also observed that good polarization isolation is obtained since at these frequencies the isolation is better than 10 dB over the entire working range (typically ±60° about the main radiation axis).

The measurements shown in Figures 5, 6A, 6B, 7A, and 7B have been associated with gain measurements so as to establish a balance sheet for the gain of the antenna shown in Figure 4 compared with two calibrated antennas, one in the band 20 MHz to 200 MHz and the other in the band 100 MHz to 1 GHz. This balance sheet is summarized in the following

table. The table also gives an estimate of gain on the basis of the measured patterns and an evaluation of resistive and of mismatch losses, thereby enabling the set of results obtained to be correlated and establishing the capacity of the antenna made in this way to cover the low frequency range while presenting qualities of compactness or indeed of miniaturization that would be inconceivable if the fundamental principles of the invention were not applied.

F	30	50	75	100	200	300	400	500	1000
V1	-21	-22	-4.10	-5.20	-0.90	-	-	-	-
V2	-	-	-	-	-2.00	-1.00	+0.50	+2.00	+4.0
D	-	-	-	0	1.00	2.00	2.50	3.0	4 to 5
M	-	-	-	-4.3	-2.0	-1.65	-1.65	-0.50	-0.30
R	-	-	-	-1.0	-1.0	-1.0	-0.50	-0.50	-0.30
G	-	-	-	-5.30	-2.0	-0.65	+0.35	2.0	3.4 to 4.4

where:

F = frequency (in MHz); V1 = Vivaldi gain antenna 1 (in dBi); V2 = Vivaldi gain antenna 2 (in dBi); D = pattern directivity (in dBi); M = mismatch losses (in dB); R = resistive losses (in dB); and G = estimated gain (in dBi).

Thus, it can clearly be seen that although it has mediocre matching ability below 100 MHz, the detection ability of the antenna of the invention (acting as a sensor) is entirely respectable, and this continues down to 75 MHz, where it presents a gain of -4 dBi.

This makes it possible to design a device having excellent sensitivity down to 100 MHz, using an elementary antenna whose dimensions do not exceed the following at λ_0 (75 MHz) = 4000 mm:

W_a = 570 mm = $0.14\lambda_0$, and L_{tot} = 330 mm = $0.0825\lambda_0$

The corresponding device is shown diagrammatically in following Figures 8A and 8B which applies to a listening

system for locating signals over a wide band at low frequencies.

Figure 8A is a diagrammatic perspective view of one example of an array of Vivaldi antennas of the invention made up of three antennas (111, 112, 113) as shown in Figure 4, which are rigidly fixed to a beam Q made of dielectric material. The three unit antennas (111, 112, 113) are disposed so that their main axes (z_1, z_2, z_3) are mutually parallel and perpendicular to the axis $\underline{y}$ of the beam Q. These planar antennas are oriented at an angle γ relative to the y-axis, that is selected in this example so that $\gamma = 45°$ in order to optimize the compactness of the assembly. Each unit antenna (111, 112, 113) has the same dimensions W_{tot} and L_{tot} as in the example of Figure 4, i.e.: W_{tot} = 600 mm, and L_{tot} = 330 mm.

The distance between the axes z_1 and z_2 is D1, and the distance between the axes z_2 and z_3 is D2. The dimensions of the beam Q are length D3, thickness δ, and width D. The dimensions of the beam are not critical, but they must be selected to impart sufficient stiffness to the assembly to enable localization to be performed by interferometric techniques.

Figure 8B is a diagrammatic plan view as seen from above showing the same example of an array of Vivaldi antennas as is shown in Figure 8A. In this figure, the same antenna system can be seen in the same disposition using the same references and the same dimensions as in the preceding figure. The description of this Figure is therefore identical to that of above Figure 8A.

Measurements have been performed on the listening system as shown in Figures 8A and 8B, and they are given in accompanying Figures 9, 10A, and 10B. In the measured system, the dimensions marked on Figures 8A and 8B had the following values, in millimeters:

L_{tot}	W_{tot}	$\gamma(°)$	D1	D2	D3	δ	D
350	600	45	780	1020	2000	30	200

Given the initially selected distances of 780 mm and 1020 mm, it is to be expected that coupling phenomena between the two antennas situated at less than 0.25λ should be of small magnitude if it is desired to operate to 100 MHz in phase detection ($\geq 0.20\lambda$ for 75 MHz). Phase detection is necessary when performing radio location by interferometer techniques.

Figure 9 shows coupling measurements performed on the antenna array system of Figures 8A and 8B. The two curves (F, G) plotted in this figure show the relative level of a signal on one or other of the peripheral antennas (111, 113) situated at 780 mm and at 1020 mm respectively from the central antenna (112), and as compared with the level of a signal on the central antenna (112).

It can be seen that the entire curve F over a frequency band extending from 130 MHz to 1010 MHz is below -20 dB, and that most of this curve F is below -25 dB relative to the central antenna situated at a distance of 780 mm. It can also be seen that the entire curve G in the same frequency band running from 130 MHz to 1010 MHz is below -25 dB, and that most of said curve G is at less than -30 dB or even -35 dB relative to the central antenna situated at a distance of 1020 mm.

As for the antenna radiation patterns shown in figures 10A and 10B, the measurements were performed at 450 MHz using the central antenna (112). The four curves (1', 2', 3', 4') should be compared with measurements performed on the antenna on its own as shown in Figures 7A and 7B by comparing corresponding curves (1, 2, 3, 4).

As in Figures 7A and 7B, Figure 10A shows antenna radiation patterns for crossed polarization (2') and for coplanar polarization (1') for the array of Figures 8A and

8B in the E plane; while Figure 10B shows the antenna radiation patterns in crossed polarization (4') and in coplanar polarization (3') for the array of Figures 8A and 8B in the H plane. The curves of Figures 10A and 10B and of Figures 7A and 7B respectively are thus directly comparable. This comparison leads to the following conclusion: the differences are insignificant and within the order of accuracy and reproducibility for measurements at these frequencies. Interaction between the antennas does not give rise to significant disturbance in the radio characteristics of the antenna.

Figure 11 is an electronic circuit diagram of a wideband listening system of the invention which can be compared with the prior art listening system shown in Figure 2. From Figure 5 and from the table of performance as a function of impedance matching for the antenna of the invention, it can be seen that the antenna of Figure 4 provides performance that is satisfactory simultaneously in sensitivity and in bandwidth, without requiring a special matching circuit between the receiving antenna (11) and the low noise amplifier (8). The diagram of the listening system of the invention shows more clearly the two advantages of the invention over the prior art: by omitting the matching circuit (9, Figure 2), the signal losses and the noise due to the matching circuit 9 are also lost.

The measurements shown in the above figures demonstrate the advantages of the invention over the prior art: small size, wide frequency band at low frequencies, low coupling levels between radiating elements and the environment, or between radiating elements, good sensitivity and directivity, simplicity of antenna structure and of antenna installation within an array of antennas on a moving platform, good stability of radio characteristics as a function of frequency, and elimination of an impedance matching circuit together with the losses and the noise that are to be associated therewith.

CLAIMS

1/ An instrument for listening to radio signals over a very wide listening band in low band, said system being designed to be installed on board a moving platform, said system comprising at least one electromagnetic sensor and a low noise amplification system associated with each sensor, the system being characterized in that said sensor is derived from a slot line, and said slot line has a profile of variation in the width of the slot along its length.

2/ A listening system according to claim 1, characterized in that said profile of variation is linear.

3/ A listening system according to claim 1, characterized in that said profile of variation is exponential and said sensor is a "Vivaldi" type antenna.

4/ A listening system according to claim 3, characterized in that the maximum width of said slot at the widest end of said Vivaldi type antenna is of the order of $\lambda_0/3$, where λ_0 is the wavelength of the lowest frequency F_0 of said listening band.

5/ A listening system according to claim 3 or 4, characterized in that the overall length of said Vivaldi type antenna $L_{tot} = \lambda_0/4$.

6/ A listening system according to claim 3 or 4, characterized in that the overall length of said Vivaldi type sensor, $L_{tot} = \lambda_0/8$ for a frequency F_0 of 100 MHz.

7/ A listening system according to claim 3 or 4, characterized in that the overall length of said Vivaldi type sensor $L_{tot} = \lambda_0/12$, for a frequency F_0 of 75 MHz.

8/ A listening system according to claim 1, characterized in that said listening system comprises a plurality of electromagnetic sensors according to any preceding claim.

9/ A listening system according to claim 8, characterized in that said plurality of sensors is disposed in an array to implement an interferometer listening system for radio signals, enabling the signals detected to be located.

10/ A listening system according to claim 8 or 9, characterized in that said sensors are spaced apart by a distance D between adjacent sensors of at least $D > 2 \times L_{tot}$.

11/ A location system including a listening system according to any one of claims 1 to 10.

12/ A system for receiving electromagnetic radiation, substantially as herein described with reference to, or as shown in, any of Figures 4 - 11 of the accompanying drawings.

Patents Act 1977 Examiner's report to the Comptroller under Section 17 (The Search report) -26-	Application number GB 9417709.4
Relevant Technical Fields (i) UK Cl (Ed.M) H1Q (QDW, QDX, QHC, QHE, QHX, QDU) (ii) Int Cl (Ed.5) H01Q 13/08, 13/10	Search Examiner J E EVANS Date of completion of Search 1 DECEMBER 1994
Databases (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii)	Documents considered relevant following a search in respect of Claims :- 1-12

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Category	Identity of document and relevant passages		Relevant to claim(s)
X	GB 1601441	(PHILIPS) see page 1, lines 27 to 29 and page 4, lines 7 to 19	1 to 3
X	EP 0477951 A2	(HUGHES) see abstract	1, 3
X	EP 0301216 A2	(BALL) see abstract and Figures 2a, 5, 10a	1, 3, 8, 9
X	US 5227808	(DAVIS) see Figures 1, 2 and 5	1, 3, 8, 9

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